Energy Mental Models: Mechanics through Electromagnetism

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Abstract: We investigated students' mental models for energy, and changes in these models in going from mechanics to electromagnetism contexts. We interviewed students in a two-semester calculus-based physics course. Our research design included semi-structured interviews with demonstration. Based on our findings in the interviews we are developing a first version of an 'Energy Mental Model Inventory.'

Introduction

The concepts of matter and energy are two fundamental concepts in science. Matter is relatively easy to teach, but not so energy. Energy is an abstract concept that cannot be associated to something. Several authors have focused on the teaching of the energy concept [1-4]. Other authors have researched on what students learn about energy [5]. In this work, in progress, we focus on mental model(s) students might use for understanding the concept of energy; that is what knowledge structure(s) (if any) a student uses to understand, explain and/or make predictions on problems related to energy? [6]

Research Goals & Methodology

The overarching goal of our research is to develop a multiple-choice instrument – a model inventory that allows educators and researchers to probe the mental model(s) students use in a variety of contexts. This inventory will be a tool for instructors that can be used to tailor a class to help the students in the development of an acceptable mental model(s).

To develop such an instrument, we began by exploring the knowledge structures that students use. We conducted in-depth interviews. We interviewed nine students from a calculus-based physics class, four times over a two-semester course sequence. We interviewed one student at the time. We proceeded in two phases: phase I during the first semester when mechanics topics were covered, and phase II during the second semester when electricity and magnetism were covered. For phase I we used semi-structured interviews with demonstrations. The interviews were conducted after mechanical energy topics were covered in class. With the results from these interviews we developed a short (six questions) multiple-choice inventory. In phase II we used only semi-structured interviews.

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Phase I :Mechanics.

Research Instruments

The interview protocols for the first semester were based in laboratory activities. The students performed the experiments based on a set of guidelines. We used a Predict-Observe-Explain (POE) sequence. The contexts for the first interview were:

1. *Loop the loop*: the student releases balls of different materials (metal, plastic and rubber), starting at different heights.
2. *Dynamic carts sliding on tracks*: the student releases two dynamic carts from different heights. The mass of the carts can be changed. We tell the student that friction is negligible.
3. *Glider and air-track*: the student uses a horizontal frictionless context. The air-track is level so that gravity is not an issue. The glider is launched using rubber bands at the ends of the track.
4. *Spring board and wood block*: A wood block is launched using a spring attached to a wood board. In this context friction is important.

After the student has performed the activity we asked him/her to explain the outcome. When the student did not use energy on their explanation we prompted him/her to use energy. Then we made sure the student was comfortable using energy to explain the activity.

The protocol for the second round of interviews was similar to the first one. Again we used the POE sequence. The contexts were:

1. *Rotation*: the student uses a rotation apparatus

2. *Newton's cradle*: the student uses "balance balls"
3. *Latent heat*: the student uses a thermos with hot, room temperature, cold and frozen water.

Research Findings

The textbook used in this calculus-based physics class is Halliday-Resnick-Walker, 6th edition [7]. The concept of energy is introduced in chapter 7. The textbook states that "a clear definition for it [energy] is difficult to write… Energy is a number that we associate with a system of one or more objects." Thus the introduction of energy might not be complete clear to a student, but it states that energy is associated with a system. We found that our students use the idea of energy in association with properties of an object or its situation. The most interesting statements brought up by the students:

1. *Potential Energy (gravitational) is due to position (height, with a reference point)*
2. *Objects in motion release energy, by conservation of energy*
3. *The word "energy" implies motion*
4. *Energy transforms (in set amounts)*
5. *Energy is a form of force; the more energy the more acceleration*
6. *Energy has a direction (a sign)*
7. *Energy has a reference point (absolute zero)*
8. *Energy depends on force, it is transferable*
9. *Thermal energy (due to atomic motion)*
10. *Heat and Cooling energy*
11. *An object has energy if it can act on something*

Using these ideas expressed by the students, and from the requirements for a mental model [8] we concluded that students use a single energy mental model in mechanics. We labeled this model "mechanical energy" model because the students relate the energy concept mainly to motion. We identified 4 aspects, or elements, that form the mechanical energy model:

1. *Positional:* when an object (in a system) has energy due to its position and size.
2. *Kinetic*: when an object is in motion (either macroscopic or microscopic).
3. *Transitional*: the substance can transform from one form to another (ice to water) or can influence another substance (ice cools water).
4. *Conservation*: energy transforms from one form to another.

An interesting note is that historically the word "energy" was used in an everyday language with the meaning of "vigorous activity" before it was introduced in physics by William Thomson in 1852 [9].

Phase II Electricity and magnetism.

Research Instruments

In a traditional second semester of a physics course the term energy is no longer emphasized. Energy is used in the context of electric and magnetic fields, but it is not brought up on discussing circuits. For example it is not emphasized that *voltage* is a measure of electric potential energy per unit charge, or that *power* is a measure of electrical energy per unit of time. Energy does not make an appearance in any of the electrical circuit formulas but the concept of energy is definitely implicit in other topics. The protocol of first interview focused on electric and magnetic fields. The first set of questions was in the context of a sphere with positive charge and mass m, starts at rest on a uniform electric field E. The questions were:

1. Would the sphere have any kind of energy?
2. If it does not have energy, explain why.
3. If it does have energy, explain why.

a. What kind of energy does it have?
b. Why does it have this kind of energy?

4. Consider a sphere with negative charge; would your answers to the previous questions change?
5. Consider a sphere with less mass. Would your answers to the previous questions change?
6. Does its energy change if I were to double/halve the charge of the sphere/
7. Does its energy change if I were to double/halve the strength of the E field?

The second set of questions was related to a sphere initially moving at a constant speed v. The third and fourth set relate to similar situations but in a region with a uniform magnetic field B. The students were also asked

to explain their understanding of electric potential energy, and gravitational potential energy.

In the second round of interviews we focused on circuits. The first set of questions related to a light bulb connected to conducting rails in a uniform magnetic field B. With these questions we explored the concepts of energy stored in a magnetic field, light energy and heat. The questions were:

1. Describe what happens in this set up when the rod moves.

a. When the does not move?

2. Is there any kind of energy involved?
3. If there is,

b. What kind-s (form-s) of energy is it?

c. Are these forms related to each other?

d. Is this energy the same all the time?

e. Explain what is the source, and how the energy is used

4. Would there be a change in energy if we change the magnitude of the magnetic field, the speed of the rod, and/or the length of the rails?

The second and third set of questions relate to a light bulb and a resistor connected to a battery. Finally, the fourth set of questions was about an L-C circuit, where the capacitor had an initial charge q. We asked the students to compare this circuit with a pendulum and to draw an analogy between them using energy.

Research Findings

The interviews were conducted after the students have received instruction on electric fields, magnetic fields, and induction. They solved homework problems related to magnetic potential energy of a magnetic dipole, and to electric and magnetic stored energies. On the first interview only one student talked about magnetic potential energy of the sphere in the magnetic field. All other students considered the problem from a mechanics point of view. The common statements made by them relate to the sphere having a potential energy because "the sphere is at rest", or because "the sphere is in an electric field and it wants to move." Both of these statements are related to aspects from the mechanical energy model. The second one uses the concept of charges moving in an electric field. When the context included the sphere with an initial constant speed, invariably all the students stated that "it has a kinetic energy, because it is moving." Two students brought up the work-energy theorem; in the context of magnetic fields, where if the sphere is at rest then there is not a force on it consequently no work is being done on the sphere and no change from potential to kinetic energy occurs. The main relation that students saw between gravitational potential energy and electric potential energy is that both are stored energy, though no explanation of where the energy is stored could be given. Two students brought up an analogy between gravitational potential energy and electric potential energy; "electric potential energy is analogous to a ramp for electrons." This analogy might have been introduced in this class or in an electrical engineering class.

In the second round of interviews the students responses again included ideas from the mechanical energy model. This time they also brought up ideas on thermal energy, heat, light energy, and potential energy of the electric field. Most often they related voltage to potential energy and current to kinetic energy. The students justified these ideas with the fact that voltage is a stored energy and current is related to motion. In the set of questions related to a battery connected to a light bulb or a resistor; students talked of light energy, heat, stored energy in the battery as chemical energy, and current as kinetic energy. The students also talked about the thermal energy in the resistor related to P=IV (the radiated power equal the current times the voltage). They used dimensional analysis to justify their idea of energy involved on the circuit, other than in the battery. Most likely this is a consequence of homework problems related to dissipation of energy. Finally, on an L-C circuit one student pointed out that the capacitor stores energy on the electric field between its plates. Everyone else had the idea that the capacitor stores potential energy; then it is given to the inductor as kinetic energy. The students confirmed that they referred to aspects of the mechanical

energy model. We emphasized to the students that the L-C circuit is in an electromagnetic context. None of the students brought up the ideas of electric and magnetic stored energies in the capacitor and inductor. The main results from these interviews :

1. Students transferred the aspects of potential and kinetic energy from the mechanical energy model to electromagnetism contexts.
2. Other types of energy are considered, like heat, light, thermal and electric energy. The relation among them is conservation of energy.
3. Electric potential (voltage) is considered a type of potential energy, because it can be stored; and current is considered a type of kinetic energy because it relates to motion.

The ideas of energy stored in an electric and magnetic field are not used by the students, perhaps because of the level abstraction or because they have not made a connection between the idea of gravitational potential energy and the gravitational field.

Energy inventory

Thus far we have developed a six questions multiple-choice inventory for the mechanics contexts. It is our goal to develop one for the electromagnetism contexts and apply to our students. These inventories differ from others [10,11] in that we do not focus on if the students know definitions of energy, rather in how the students use the concept of energy.

Conclusions

We researched the energy mental models that students use in a physics course, from mechanics to electromagnetism. In the mechanics contexts, we identified four aspects that form one energy model. We labeled this model "mechanical energy" model. We found students transferred their model from mechanics to electromagnetic contexts. The aspects transferred are position, kinetic (motion) and conservation. In electromagnetism contexts students use other forms of energy in their explanations. Forms like heat, light, thermal, and electrical energy. But they do not use the ideas of energy stored in an electric and magnetic field. More research is required in electromagnetism contexts.

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